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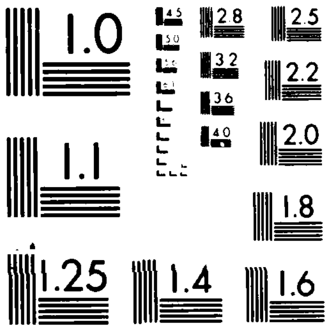

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EVALUATION OF A THERMOLUMINESCENT DOSIMETER FOR PERSONNEL MONITORING IN THE NUCLEAR-RADIATION ENVIRONMENT

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ABSTRACT

Efforts to improve the responses of phosphor/polyethylene TLDs to neutrons in the 1-MeV range have been only partially successful. Some increases in response have resulted from reduction of phosphor grain size and substitution of $CaSO_4$:Tm with CaF_2:Mn or CaF_2:Dy. Reasons for the continuing low response are not fully understood.

Calculated responses of the TLDs, when located on the body, show a closer correlation with the dose received by the bone marrow as a result of exposure to a weapon spectrum than is evident for the case of flat-response dosimeters. However the TLDs exhibit a greater difference in their response to a weapon spectrum as compared with that to a pure gamma spectrum than is the case for a flat-response dosimeter. The disparity becomes even larger when the dose measured by the dosimeters is expressed in terms of the biologically effective dose absorbed in the bone marrow. Investigation of the ability of a dosimeter, which is sensitive only to γ-rays, to provide a measure of the total bone marrow dose produced by a combined flux of γ-rays and neutrons, indicates that there is an unacceptable difference between the response to a pure gamma spectrum and that to a mixed spectrum from a weapon.

RÉSUMÉ

Les tentatives pour améliorér la réponse aux neutrons des détecteurs thermoluminescents (DTL) au phosphore/polyethylène dans la gamme de 1-MeV n'ont réussi que partiellement. Nous avons obtenu une hausse de la réponse en réduisant les grains du phosphore et en substituant le $CaSO_4$:Tm par le CaF_2:Mn ou par le CaF_2:Dy. Nous ne comprenons pas encore pleinement les raisons pour lesquelles les réponses restent basses.

La dose calculée à partir des réponses des DTL placés sur la surface du corps nous donne une corrélation plus étroite avec la dose reçue par la moëlle osseuse après l'exposition à une arme nucléaire qu'avec la dose mesurée à l'aide d'un dosimètre à réponse uniforme. Par contre les DTL montrent une plus grande différence dans la réponse à un spectre d'arme nucléaire que les dosimètres à réponses uniformes lorsque comparés à un spectre de rayon gamma. Cette différence est encore plus marquée lorsque la dose mesurée par les dosimètres est exprimée en terme de dose biologiquement efficace absorbée dans la moëlle osseuse. L'étude de la capacité d'un dosimètre, sensible uniquement aux rayons gammas, à fournir une mesure de la dose totale reçue par la moëlle osseuse et produite par un flux combiné de rayons gammas et de neutrons, indique qu'il y a une difference inacceptable entre la réponse à un spectre de rayons gamma et celle à un spectre combiné d'une arme nucléaire.

INTRODUCTION

A thermoluminescent (TL) dosimeter, designed for combined measurement of the dose from gammas and fast neutrons, has been described in earler DREO reports. The last of these (Facey et al. (1)) outlines the theoretical basis of the neutron response of this dosimeter and includes neutron response measurements at specific energies for a dosimeter comprised of the TL phosphor $CaSO_4$:Tm embedded in a matrix of polyethylene. The present report gives the results of efforts to improve on the fast-neutron response by using very fine powders of $CaSO_4$:Tm and of two other phosphors CaF_2:Mn and CaF_2:Dy. The measured ratios of the neutron-to-gamma responses are combined with the results of calculations by Scott et al. (2) of bone marrow dose in the field of a nuclear weapon to give an evaluation of the effectiveness of these dosimeters for use by military personnel.

PREPARATION OF THE SAMPLES

The $CaSO_4$:Tm samples were prepared by mixing either 5 or 10% by weight of phosphor with very fine polyethylene powder in an ethyl alcohol slurry using an ultrasonic probe. This was hot-pressed as outlined in Ref. (1) to form the sample material. Standard (fine) samples, made with 10% $CaSO_4$:Tm powder of grain size up to 10 μm, were used throughout as a reference for monitoring improvement of response by further reduction in phosphor-particle size. The finest powder which could be obtained was estimated to contain only particles less than about 2 μm in diameter and is referred to as ultrafine (UF) powder.

The CaF_2:Mn and CaF_2:Dy dosimeters were made from powders obtained from Harshaw Chemicals. These were reduced in size by hand grinding and ultrafine powders were obtained by removing all but the very fine particles by settling in water. These powders contain only particles estimated to be less than about 1 μm in diameter. Annealing at 400^{0}C for 1 hour was carried out before mixing with the polyethylene.

MEASUREMENT PROCEDURE

Measurements were made with monoenergetic neutron sources of energies 1.0, 2.0, 5.0 and 14.9 MeV and with ^{60}Co gammas. The reader is referred to Ref. (1) for measurement of these sources. The fluence-to-kerma conversion factors (for Reference Man) (Kaul and Jarka (3)) of 2.30, 3.00, 4.32 and 7.05 x 10^{-9} rad/(n/cm^2) for the four energies in the order above differ slightly from the factors used in Ref. (1). After irradiation all samples were annealed at 100^{0}C and read in a nitrogen atmosphere by a Harshaw reader.

RESULTS OF MEASUREMENTS

While the TL reader output can be assumed to be proportional to the TL emission from the irradiated samples, the units are arbitrary and the relation between the TL emission and reader output is inclined to drift from day to day. Consequently, it is meaningful to express the dosimeter response as a ratio, and each neutron-response measurement is related to a gamma-response measurement made for samples of the same dosimeter which were read on the same day. Results are plotted in Fig. 1 for phosphor/polyethylene dosimeters made using ultrafine powders of the three phosphor materials and also for the fine powder of $CaSO_4$:Tm which has somewhat larger grains than the ultrafine powders. These response ratios are in terms of free-in-air (FIA) tissue kerma for both types of radiation.

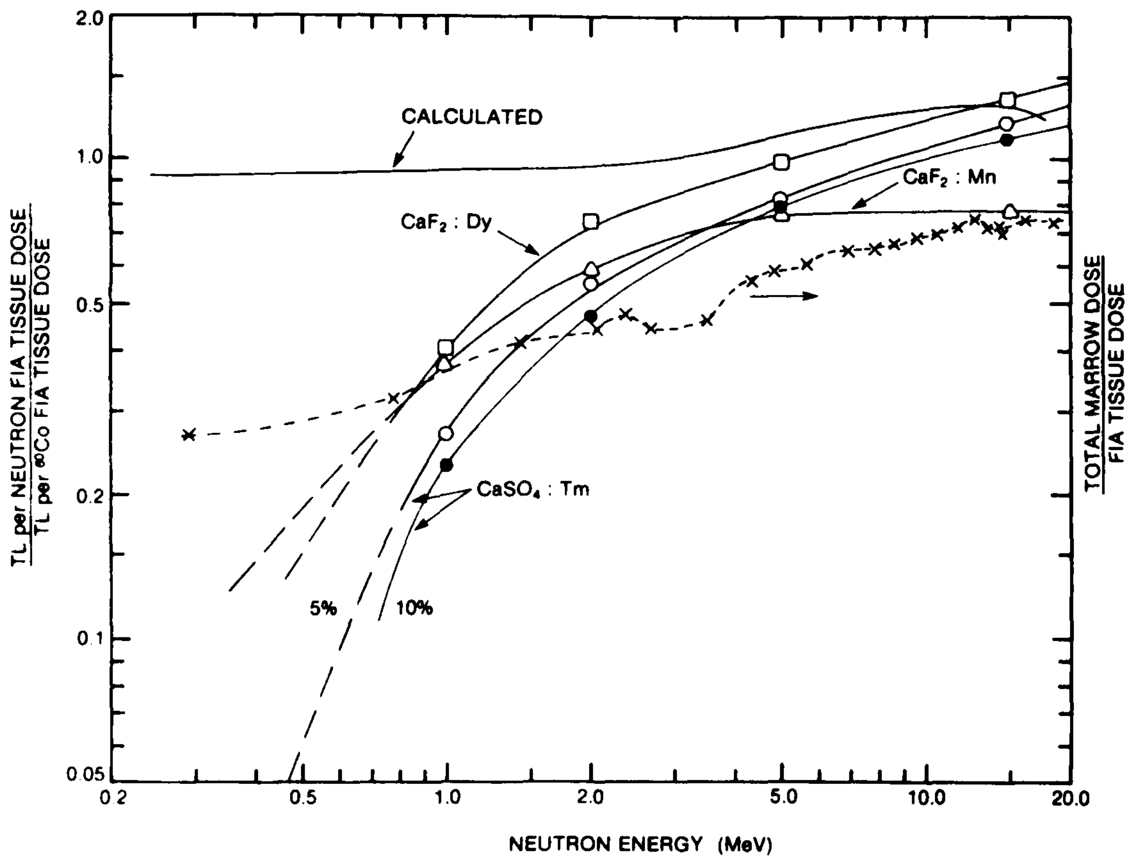

Fig. 1. Experimental response ratios for the three ultrafine (5%) phosphor/polyethylene TLDs and the fine (10%) $CaSO_4$:Tm TLD, and also the calculated response for the $CaSO_4$:Tm TLD, left hand scale. Total bone marrow dose due to neutrons per FIA tissue dose, right hand scale.

The dosimeters with the fine $CaSO_4$:Tm correspond to those used in Ref. (1) and the results here agree with the previous measurements except at 2 MeV. The previous value at this energy was based on a single run and according to later measurements appears to be about 25% high. The improvement in neutron response by further reduction in grain size of the $CaSO_4$:Tm powder is disappointing with only about 15% increase being realized at 1 and 2 MeV. Some of this should result from reduction in the fraction of phosphor from 10 to 5%. A number of dosimeter pellets have been made with this ultrafine powder with fairly consistent results. It is hard to attribute the relatively low neutron response at 1 and 2 MeV to particle size or to poor mixing of the phosphor in the polyethylene as suggested in Ref. (1).

The response ratios for the two CaF_2 phosphors indicate that factors other than particle size determine the response as a function of neutron energy. Both these phosphors show better neutron response at the lower neutron energies than did the $CaSO_4$:Tm. At 14.9 MeV the response ratio for the CaF_2:Mn is less than that for the $CaSO_4$:Tm whereas this ratio is highest for the CaF_2:Dy dosimeter. The measured response ratio for the $CaSO_4$:Tm at 14.9 MeV approximates the ratio predicted on the basis of the energy absorbed in the phosphor; the variation with energy of the calculated ratio is indicated in Fig. 1. These calculations involve ratios of the doses absorbed in the dosimeter and in tissue for both gammas and neutrons, as well as the relative stopping powers of the $CaSO_4$ grains and the polyethylene for both the knock-on protons and the gamma-produced electrons. For ^{60}Co gammas a ratio of 0.77 was used for the dose absorbed in the phosphor grains in polyethylene relative to the tissue dose.

POSSIBLE REASON FOR LOW NEUTRON RESPONSE

For gamma radiation the dosimeter appears as a fairly uniform medium as regards photon-energy absorption (except at very low energies) and the range of the ionizing electrons is much larger than the dimensions of the phosphor particles. On the other hand, the neutron energy is absorbed primarily by transfer of energy to hydrogen atoms in the polyethylene and the resulting knock-on protons then act as the ionizing particles. The phosphor grains can be considered as cavities in the polyethylene only if they are small in relation to the ionizing-particle range. Where this condition holds for the knock-on protons, the neutron energy will be absorbed in the phosphor, according to the average absorption of neutrons in the dosimeter, with allowances being made for relative stopping powers of the phosphor and the polyethylene. But, since the proton range is proportional to the neutron energy, an energy dependence can be expected where the protons produced are of ranges comparable to the diameter of the phosphor particles. This was discussed in some detail in Ref. (1) where it was estimated that a particle diameter of 1 μm should not degrade the response unduly at 1 MeV. This, of course, presumes that the particles are well dispersed within the polyethylene.

Associated with the relatively short range of protons compared with electrons is their higher linear energy transfer (LET) resulting in higher ion densities being produced along their tracks. LET effects in TL phosphors have been reported (for example Jähnert (4) and Hübner et al. (5)) wherein the response is reduced with increasing LET. 1-MeV protons for example, have an LET which is about two orders of magnitude greater than that for the same energy electrons. However, no LET effect on the response is apparent at 14.9 MeV in Fig. 1 for $CaSO_4$:Tm where the LET of the protons produced by the 14.9-MeV neutrons differs by almost two orders of magnitude from the LET of the electrons produced by the ^{60}Co gammas. Can the drop in response at the lower neutron energies ($\sim$1 MeV) be explained by a further increase in LET by a factor of about 3 ? This would require some sort of saturation effect to be taking place within this variation of LET for this phosphor.

The lower response of the CaF_2:Mn dosimeter to 14.9-MeV neutrons indicates that there may be an LET effect which leads to a reduction in response to the resulting knock-on protons in that phosphor, and further reduction with neutron energy could be explained on that basis.

The LET effect was investigated by comparing responses to 4.3-MeV alpha-particles with that to ^{60}Co gammas. Differences in the alpha/gamma response ratio were noted for different size gradations of CaF_2:Mn powders and for polycrystalline CaF_2:Mn chips from Harshaw. The chips and coarse powder gave alpha/gamma ratios of about 0.31 and 0.53, an intermediate powder a ratio of 0.56, and fine and ultrafine powders ratios of 0.82 and 1.05. These changes with particle size represented a reduction in gamma response rather than an increase in response to alphas. Furthermore, lower responses were observed (except for the ultrafine powder) for the alphas when their energy was reduced to 1.4 MeV by attenuation in nickel foils. For the chips and powders, in the above order, ratios of 0.19, 0.36, 0.41, 0.72 and 1.2 were found. These alphas have only a slightly larger LET than the 4.3-MeV alpha-particles. A reduction in response because of reduced range is indicated, and it can be postulated that the lower alpha/gamma response ratio for the larger particles is at least partly due to reduced response near the particle surface or near the surface of the polycrystalline dosimeters. This is not observed where the entire particle is irradiated as is the case for the smaller phosphor grains. This does not rule out an LET effect for this phosphor, but demonstrates that a reduction in response at the phosphor surface can be misinterpreted as an LET effect.

EVALUATION OF COMBINED DOSIMETERS

The response of the thermoluminescent dosimeters shown in Fig. 1 appears to leave much to be desired. However, an evaluation for military personal dosimetry requires combining these responses with the radiation spectra likely to be encountered and with the response of critical organs to these spectra. For these purposes the critical organ is generally considered to be the blood-forming organs located in the red bone marrow. If we look at the dose absorbed in this organ as a function of neutron energy, we see, as in Fig. 1, that this dose, also, drops off with neutron energy and tends to compensate for the dosimeter response.

These dosimeters were evaluated in conjunction with calculations made in Ref. (2) in which bone marrow doses and doses at various dosimeter positions were calculated for weapon spectra. To conform with weapon spectra available (Robitaille (6)) DLC-31 energy groups were used. From Fig. 1 the response ratios R_{ni} corresponding to the mid-points of the energy intervals E_i of the DLC-31 data-library structure were determined. For the neutron fluence spectra of interest, expressed in the DLC-31 format, the corresponding neutron tissue kerma spectral components D_{ni} were calculated using the FIA tissue kerma factors for Reference Man (Ref. (3)). For each TLD the integrated neutron response $\Sigma\, D_{ni}\, R_{ni}$ was calculated, from which was determined the weighted averge neutron response per total free-in-air (FIA) tissue dose due to neutrons given by

$$\overline{R}_n = \frac{\Sigma_i\, D_{ni}\, R_{ni}}{\Sigma_i\, D_{ni}},$$

appropriate to the particular neutron spectrum being considered. The $\overline{R}_n$ values obtained for the various dosimeters are summarized in Table I

Table I: The Spectrum-Weighted Average Neutron Response $\overline{R}_n$ of Three DREO Dosimeters per Total FIA Tissue Dose Due to Neutrons, for Four Different Spectra. SFW = Standard Fission Weapon and ERW = Enhanced Radiation Weapon, Ref. (6). SAI = Science Applications Inc., Ref. (2).

Neutron Spectrum / Dosimeter	DREO 1100 m	SAI 1012.5 m	SFW 1000 m	ERW 1000 m
CaF_2:Dy	0.457	0.457	0.292	0.717
CaF_2:Mn	0.392	0.400	0.274	0.532
$CaSO_4$:Tm	0.345	0.341	0.206	0.586

It is evident that the differences in $\overline{R}_n$ between the various spectra for a given TLD reflect differences in the general structure of the spectra. Thus in all cases $\overline{R}_n$ is highest for the ERW spectrum because this spectrum contains a larger fraction of high-energy neutrons than do the other spectra, and the dosimeters are more sensitive to such neutrons than to neutrons of lower energy, as is evident in Fig. 1. The near-equality of the $\overline{R}_n$ values for the DREO and SAI spectra is a consequence of the similarity of the two spectra, at least over the spectral region where the dosimeters are sensitive.

For a mixed gamma and neutron spectrum the effective sensitivity of a TLD in terms of its gamma sensitivity is given by

$$\overline{R} = \frac{D_\gamma + \overline{R}_n\, D_n}{D_\gamma + D_n},$$

where D_γ and D_n are the components of the FIA tissue kerma for gammas and neutrons respectively, and $\overline{R}_n$ is the appropriate TLD response applicable to the neutron component of the spectrum.

Since it is desired to relate the reading of a TLD to the bone marrow dose, the dosimeter response R_m can be defined as the total dose measured by the dosimeter (FIA) relative to its gamma response as a fraction of the average dose absorbed in the bone marrow. Thus

$$R_m = \frac{D_{\gamma d} + \bar{R}_n D_{nd}}{D_{\gamma m} + D_{nm}}$$

where the subscripts d and m indicate doses received by the dosimeter and by the bone marrow respectively. However when a TLD is worn on an individual's body the dosimeter does not then measure the FIA dose since the dose received by the dosimeter depends on its orientation with respect to the source of the incident flux, being either shielded by the body or subjected to additional flux scattered from the body; in particular the gamma dose measured by the TLD includes a component made up of escaping gammas produced by n-γ interactions in the body.

Tabulated data are available (Ref. (3)) which give the bone marrow dose deposited in a standing man by an isotropic incident fluence, the data being presented for each of the 37 neutron and 21 gamma-ray energy groups of the DLC-31 format. The tabulated quantities include neutron (n-n) and gamma (n-γ) dose depositions per unit incident neutron fluence, and gamma-ray dose (γ-γ) per incident gamma-ray fluence. Thus for any given incident spectrum it is possible to calculate the marrow dose components D_{nm} (comprising the n-n and n-γ contributions) and $D_{\gamma m}$ and hence the total marrow dose D_m. Less comprehensive data are also presented, for selected weapon types, in the form of coefficients $F_{\gamma-\gamma}$, and F_{n-n} and $F_{n-\gamma}$ representing the marrow dose as a fraction of the incident FIA dose components, from which the total marrow dose could be estimated. Unfortunately no similar data sets are available from which dosimeter responses can be calculated for cases where the dosimeter is located on the body of an individual.

Dosimeter Response Relative to the Average Total Marrow Dose

Other data are available (Ref. (2)), however, in the form of graphs of the gamma-ray and neutron doses, $D_{\gamma d\theta}$ and $D_{nd\theta}$, at a dosimeter placed at various positions on the body for different angular orientations of the body with respect to a hypothetical 5-kt weapon burst at a distance of 1.2 km. Examples of the calculated gamma and neutron energy spectra at 1.01 km produced by this source are also given, and are here referred to as the SAI spectra. The dosimeter data are plotted for STANDING, SEATED and PRONE man and for four dosimeter locations on the body. These are not FIA doses, but rather the doses as modified by the presence of the body, as indicated previously. Since the doses can be read off the various graphs, the gamma response of a dosimeter

on the body is obtained directly and the appropriate neutron response can be calculated using $\overline{R}_n$, the spectrum-weighted average neutron response of the particular dosimeter per total FIA dose due to neutrons, as given for the SAI neutron spectrum in Table I. Graphs of the average total marrow dose, $D_{m\theta}$ as a function of angular orientation are also given, and thus $R_{m\theta}$, the dosimeter response per average total marrow dose, can be calculated for any particular orientation:

$$R_{m\theta} = \frac{D_{\gamma d\theta} + \overline{R}_n D_{nd\theta}}{D_{m\theta}}$$

Summation of $R_{m\theta}$ over the N orientations considered then provides the response

$$R_m = \frac{\Sigma_\theta R_{m\theta}}{N}$$

for an isotropic exposure. It should be noted that the use of $\overline{R}_n$, as defined, in the calculation of $R_{m\theta}$ implies that the neutron component of the incident FIA spectrum is not changed significantly in shape at the location of the dosimeter by the presence of the body.

Since the data referred to above apply to the SAI spectrum it is possible to derive the angle-dependent dosimeter responses for a flat-response dosimeter of the SAI type (for which all $R_{ni} = 1$) and for the DREO dosimeters only for this spectrum. While the neutron component of the DREO spectrum is of essentially the same shape as that of the SAI spectrum, and the total isotropic marrow dose as a fraction of the total FIA dose is the same for the two spectra, the relative proportions of the FIA gamma and neutron tissue-dose components differ for the two spectra, and thus the available data cannot be applied directly to the DREO spectrum.

Typical values calculated for $R_{m\theta}$ and R_m, using the SAI spectrum, are given in Table II for the case of different locations of the $CaSO_4$:Tm dosimeter for STANDING, SEATED and PRONE MAN. It should be noted that the 90^0 orientation corresponds to the man facing the burst, or with his head toward the burst if lying PRONE. Also included is the maximum spread in the $R_{m\theta}$ values as a percentage of the isotropic response represented by R_m.

In Table III the calculated $R_{m\theta}$ and R_m values are given for the case of the flat-response SAI-type dosimeter for the same conditions as presented in Table II.

Table II: Values of $R_{m\theta}$ and R_m Calculated for the $CaSO_4$:Tm Dosimeter Using the SAI Spectrum, for STANDING, SEATED, and PRONE Man.

	Angle	Chest	Back	Chest & Back Average	Wrist Out
STANDING MAN					
	0	0.852	0.800	0.826	0.796
	45	0.910	0.745	0.828	0.823
	90	0.967	0.698	0.833	0.855
	135	0.898	0.766	0.832	0.868
	180	0.821	0.847	0.834	0.869
	225	0.675	0.884	0.780	0.793
	270	0.619	0.881	0.750	0.744
	315	0.704	0.845	0.755	0.775
Average $R_{m\theta} = R_m$		0.806	0.808	0.807	0.813
Maximum Spread as % of Average		43.2	23.0	10.4	15.4
SEATED MAN					
	0	0.799	0.893	0.846	0.821
	45	0.859	0.826	0.843	0.869
	90	0.933	0.768	0.851	0.930
	135	0.861	0.844	0.853	0.948
	180	0.797	0.942	0.870	0.959
	225	0.690	0.963	0.827	0.825
	270	0.667	0.954	0.811	0.730
	315	0.706	0.931	0.819	0.758
Average $R_{m\theta} = R_m$		0.789	0.890	0.840	0.855
Maximum Spread as % of Average		33.7	21.9	7.0	26.8
PRONE MAN					
	0	0.502	1.097	0.800	1.019
	45	0.574	1.094	0.834	1.075
	90	0.676	1.099	0.888	1.113
	135	0.781	1.070	0.926	1.072
	180	0.860	1.042	0.951	1.031
	225	0.765	1.128	0.947	1.066
	270	0.625	1.215	0.920	1.107
	315	0.552	1.155	0.854	1.059
Average $R_{m\theta} = R_m$		0.667	1.113	0.980	1.068
Maximum Spread as % of Average		53.7	15.5	17.0	8.8

Table III: Values of $R_{m\theta}$ and R_m Derived from Ref. (2) for the Flat-Response SAI Dosimeter Using the SAI Spectrum, for STANDING, SEATED, and PRONE man.

	Angle	Chest	Back	Chest & Back Average	Wrist Out
STANDING MAN					
	0	1.274	1.222	1.248	1.252
	45	1.365	1.118	1.242	1.300
	90	1.451	1.033	1.242	1.352
	135	1.337	1.158	1.248	1.392
	180	1.214	1.301	1.258	1.404
	225	0.966	1.379	1.173	1.276
	270	0.885	1.362	1.124	1.182
	315	1.024	1.308	1.166	1.196
Average $R_{m\theta} = R_m$		1.189	1.235	1.212	1.294
Maximum Spread as % of Average		47.6	28.0	11.1	17.2
SEATED MAN					
	45	1.254	1.233	1.244	1.356
	90	1.364	1.133	1.249	1.457
	135	1.237	1.264	1.251	1.508
	180	1.123	1.424	1.274	1.532
	225	0.936	1.476	1.206	1.322
	270	0.906	1.453	1.180	1.165
	315	0.982	1.422	1.202	1.192
Average $R_{m\theta} = R_m$		1.120	1.345	1.232	1.351
Maximum Spread as % of Average		40.9	25.5	7.6	27.2
PRONE MAN					
	0	0.631	1.762	1.197	1.672
	45	0.730	1.783	1.257	1.749
	90	0.890	1.815	1.353	1.815
	135	1.069	1.764	1.417	1.747
	180	1.195	1.714	1.455	1.678
	225	1.048	1.849	1.449	1.739
	270	0.825	1.981	1.403	1.807
	315	0.699	1.869	1.284	1.731
Average $R_{m\theta} = R_m$		0.886	1.817	1.352	1.742
Maximum Spread as % of Average		63.7	14.7	19.1	8.21

Extreme Values of Dosimeter Response Ratios

The representative data presented in Tables II and III indicate that there can be significant variations in $R_{m\Theta}$ depending on the posture and orientation of the individual and on the location of the dosimeter. In a tactical situation the posture and orientation of any individual at the instant of exposure will generally be unknown, and thus the range of dosimeter responses $R_{m\Theta}$ which might be encountered for a particular dosimeter location is of importance. Thus Table IV lists the maximum and minimum $R_{m\Theta}$ values, regardless of posture or orientation, which would be obtained for various dosimeter locations for the SAI dosimeter and the three DREO types. It is apparent that the variation in response is greater than 90% for a dosimeter on the CHEST, 75-90% for one on the BACK, and 50-75% for one on the WRIST, depending on the particular dosimeter. However if dosimeters are worn both on the CHEST and on the BACK the variation in the average response of the two is then only $\sim$30%.

Table IV: Maximum and Minimum Values of $R_{m\Theta}$, Regardless of Posture or Orientation, for Different Dosimeters Located at Various Positions on the Body, Calculated Using the SAI Spectrum.

Dosimeter →	SAI	CaF_2:Dy	CaF_2:Mn	$CaSO_4$:Tm
		CHEST		
Max	1.451	1.049	1.002	0.967
Min	0.631	0.524	0.512	0.502
Ratio	2.30	2.00	1.96	1.93
		BACK		
Max	1.981	1.346	1.270	1.215
Min	1.033	0.738	0.722	0.698
Ratio	1.92	1.82	1.76	1.74
		Average CHEST & BACK		
Max	1.455	1.037	0.988	0.951
Min	1.124	0.780	0.7700.	0.750
Ratio	1.29	1.33	1.28	1.27
		WRIST OUT		
Max	1.815	1.233	1.164	1.113
Min	1.165	0.695	0.683	0.730
Ratio	1.56	1.77	1.70	1.52

Table V: Maximum Spread in $R_{m\Theta}$ as a Percentage of the Average R_m Value Appropriate to an Isotropic Exposure

Dosimeter Type \ Dosimeter Location	Chest	Back	Chest & Back Average	Wrist Side	Wrist Out
STANDING					
SAI	47.6	28.[illegible]	11.1	33.0	17.2
CaF_2:Dy	44.1	24.3	10.5	31.1	16.0
CaF_2:Mn	43.6	23.6	10.5	30.8	15.7
$CaSO_4$:Tm	43.2	23.0	10.4	30.2	15.4
SEATED					
SAI	40.9	25.5	7.6		27.2
CaF_2:Dy	35.3	22.7	7.2		26.9
CaF_2:Mn	34.3	22.3	7.0		26.8
$CaSO_4$:Tm	33.7	21.9	7.0		26.8
PRONE					
SAI	63.7	14.7	19.1		8.2
CaF_2:Dy	55.8	15.3	17.4		8.6
CaF_2:Mn	54.5	15.4	17.3		8.8
$CaSO_4$:Tm	53.7	15.5	17.0		8.8

The dosimeter responses, typified by the data presented in Tables II and III for the dosimeters at various locations on the body, are summarized in Table V in terms of the difference between the maximum and minimum values of $R_{m\Theta}$ as a percentage of the R_m value appropriate to an isotropic exposure. In all cases the response of a dosimeter on the BACK shows less variation with angle than does the response of one on the CHEST, whereas the response of a WRIST dosimeter on a PRONE man shows the smallest variation of all. The average of CHEST and BACK dosimeter responses for each angular orientation shows, particularly for STANDING and SEATED man, that the spread in possible $R_{m\Theta}$ values is reduced considerably, and again suggests that the wearing of two dosimeters would lead to a more realistic estimate of the marrow dose received regardless of the orientation of the individual. For PRONE man this average response does not give an improvement over the response of the BACK dosimeter alone, being a consequence of the fact that the CHEST dosimeter responses are significantly smaller than, and do not anti-correlate as well with, the BACK dosimeter reponses as compared with the similar responses for STANDING or SEATED man. The actual values calculated for R_m, based on the average of CHEST and BACK dosimeter responses, are smallest for STANDING man and largest for PRONE man for each type of dosimeter, which suggests that if the posture of a man is not known at the time of exposure the use of this average R_m value as calculated for a STANDING man will mean that the estimated marrow dose would be too high if the man happened to be SEATED or PRONE. Thus appropriate medical treatment would probably be initiated, whereas if the estimated dose had been lower than that actually received then medical treatment might not be considered necessary, while in reality it should be provided.

FIA Isotropic Response of the Dosimeters

While, as stated previously, it is possible to evaluate the dosimeter responses at various locations on the body only for the SAI neutron spectrum, the FIA isotropic response R'_m of the dosimeters can be determined for STANDING man for any spectrum for which $\bar{R}_n$ has been calculated. Thus in this case

$$R'_m = \frac{D_{FIA} + \bar{R}_n D_{FIAn}}{D_m} ,$$

and calculated values are listed in Table VI. Also included in this table are the responses to be expected for a neutron-insensitive dosimeter ($\bar{R}_n = 0$) and for exposure to a pure gamma spectrum such as that which would be characteristic of fall-out (Ref. (2)).

Table VI: FIA Response R'_m of the Various Dosimeter Types for Isotropic Irradiation of STANDING MAN by a Number of Different Spectra.

Dosimeter \ Spectrum	DREO	SAI	SFW	ERW	Fall-out 4 Hours	Fall-out 2 Days
SAI($\bar{R}_n$=1)	1.531	1.534	1.481	1.681	1.42	1.45
CaF_2:Dy	1.100	1.022	0.881	1.323	1.42	1.45
CaF_2:Mn	1.049	0.968	0.866	1.088	1.42	1.45
$CaSO_4$:Tm	1.012	0.913	0.809	1.157	1.42	1.45
$\bar{R}_n = 0$	0.738	0.591	0.635	0.416	1.42	1.45

It will be noted that the R'_m values for the DREO dosimeters and the neutron-insensitive dosimeter are larger for the DREO spectrum than for the SAI spectrum. This again is a reflection of the fact that, while the neutron components of the two spectra are similar and the total marrow doses are the same, the FIA dose due to the gamma component constitutes a larger fraction of the total FIA dose for the DREO spectrum than is the case for the SAI spectrum. On the other hand the smallest value of R'_m occurs for the neutron-insensitive dosimeter when exposed to the ERW spectrum, being a consequence of the fact that the fraction of FIA dose due to neutrons for this spectrum is larger than for any of the other spectra.

For the case of the SAI spectrum, the FIA isotropic responses R'_m quoted above for the DREO dosimeters are between 13.1 and 16.7% higher than the previously derived R_m values for STANDING man which were based on the average of CHEST and BACK dosimeter responses for an isotropic exposure. For the flat-response SAI dosimeter, on the other hand, the calculated R'_m is almost 27% higher than the corresponding R_m value, being a consequence of the greater neutron sensitivity of this dosimeter as compared with the DREO types.

The range of values of R'_m evident in Table VI for any particular dosimeter, other than the SAI type, suggests that the FIA response of any of the dosimeters will not provide a particularly reliable indication of the marrow dose unless some conditions of the exposure are known. Thus if it was known that the exposure was to a weapon-type spectrum, as opposed to fall-out, then the range of possible dosimeter responses becomes somewhat less extreme, differing by a factor of 1.77 in the case of a neutron-insensitive dosimeter for the DREO spectrum as compared with the ERW spectrum, and a factor of 1.5 in the case of the CaF_2:Dy dosimeter for the ERW spectrum as compared with the SFW spectrum.

Consideration of the Relative Biological Effectiveness of the Dose

The response of interest which has so far been discussed is the dose measured by a dosimeter as a fraction of the average dose absorbed in the bone marrow. The latter quantity, however, is not in itself a true measure of the biological effect on the body since gamma-rays and neutrons have different relative biological effectiveness (RBE). To take account of this difference, the dose measured by the dosimeter can be considered more realistically as a fraction of the average biologically effective dose absorbed in the bone marrow where, instead of $D_m = D_{\gamma m} + D_{nm}$, the dose equivalent $DE_m = D_{\gamma m} + RBE \cdot D_{nm}$ is used in the calculation of R_m or R'_m. This modification reduces the R_m and R'_m values for a particular spectrum by a constant factor, depending on the RBE value selected, for all dosimeter types, and thus widens the disparity evident in Table VI, between the response to a weapon-type spectrum as compared with that to a fall-out spectrum for a given dosimeter. In the case where a dosimeter is sensitive to both gamma-rays and neutrons, as are the DREO types, this disparity in response cannot be modified. For dosimeters of the SAI type, however, where the gamma and neutron doses are measured by independent detectors and where the response of the neutron detector is flat, it is possible to assign any desired value to $\overline{R}_n$ such that the overall dosimeter response as a fraction of bone marrow dose equivalent for a particular weapon-type spectrum will approximate that for a pure gamma spectrum. Thus the use of independent detectors has the advantage of providing an additional parameter which can be employed to obtain a desired overall response.

ESTIMATION OF TOTAL MARROW DOSE BY MEANS OF A GAMMA-SENSITIVE DOSIMETER

Since some neutron interactions in the body give rise to secondary gamma rays, it is possible that a dosimeter which is sensitive only to gamma rays might give a response which would provide a measure of the total dose to the bone marrow produced by a combined flux of both gamma rays and neutrons. Therefore, using the previously-referred-to gamma-ray doses $D_{\gamma d\theta}$ produced by the SAI spectrum at a dosimeter placed at various positions on the body for different angular orientations θ, values for $R_{m\theta}$ and R_m were calculated for STANDING, SEATED and PRONE man and are given in Table VII. It will be noted from this table that the maximum spread in the $R_{m\theta}$ values as a percentage of the isotropic response R_m is not significantly different from the spread evident in Tables II and III for the case where the dosimeters are both neutron and gamma-ray sensitive. Table VIII lists the maximum and minimum $R_{m\theta}$ values, regardless of posture or orientation, for the various dosimeter wearing positions. It is apparent that the variation in response is less extreme than for the case of any of the neutron-sensitive dosimeters referred to in Table IV, particularly for the case of a dosimeter on the CHEST.

It will be noted in Table VII that the R_m value of 0.593 calculated for STANDING MAN for an isotropic exposure, based on the average of the CHEST and BACK dosimeter responses over the various orientations, is virtually identical with the FIA isotropic response R'_m quoted in Table VI for a gamma-sensitive dosimeter ($\overline{R}_n$ = 0) for the same SAI spectrum. It can be concluded that such an identity is a result of the fact that gamma rays generated in the body by neutron interactions compensate for those incident gamma rays which are absorbed by the body. Thus the isotropic gamma response of a gamma-sensitive dosimeter on the body, averaged over CHEST and BACK locations, approximates its FIA response for this particular spectrum.

Table VII: Values of $R_{m\theta}$ and R_m Calculated for a Gamma-Sensitive Dosimeter Using the SAI Spectrum, for STANDING, SEATED, and PRONE Man.

Angle	Chest	Back	Chest & Back Average	Wrist Side	Wrist Out
STANDING MAN					
0	0.629	0.578	0.604	0.508	0.555
45	0.670	0.548	0.609	0.586	0.572
90	0.712	0.521	0.617	0.664	0.594
135	0.666	0.558	0.612	0.679	0.592
180	0.615	0.607	0.611	0.679	0.588
225	0.521	0.623	0.572	0.638	0.538
270	0.480	0.627	0.554	0.614	0.513
315	0.535	0.601	0.568	0.555	0.523
Average $R_{m\theta} = R_m$	0.604	0.583	0.593	0.615	0.559
Max Spread as % of Average	38.4	18.2	10.6	27.8	14.5

Table VII Continued

SEATED MAN

0	0.609	0.650	0.630	0.582
45	0.650	0.612	0.631	0.612
90	0.705	0.575	0.640	0.653
135	0.663	0.622	0.643	0.653
180	0.625	0.688	0.657	0.657
225	0.560	0.692	0.626	0.564
270	0.542	0.691	0.617	0.501
315	0.560	0.672	0.616	0.529
Average $R_{m\Theta} = R_m$	0.614	0.650	0.632	0.594
Max spread as % of Average	26.5	18.0	6.5	25.6

PRONE MAN

0	0.434	0.746	0.590	0.675
45	0.492	0.732	0.612	0.720
90	0.564	0.722	0.643	0.744
135	0.629	0.704	0.667	0.716
180	0.684	0.688	0.686	0.691
225	0.616	0.748	0.682	0.712
270	0.520	0.811	0.666	0.739
315	0.474	0.778	0.626	0.705
Average $R_{m\Theta} = R_m$	0.552	0.741	0.646	0.713
Max spread as % of Average	45.3	16.6	14.9	9.7

Table VIII: Maximum and Minimum Values of $R_{m\Theta}$, Regardless of Posture or Orientation, for a Gamma-Sensitive Dosimeter Located at Various Positions on the Body, Using the SAI Spectrum.

	Chest	Back	Chest & Back Average	Wrist Out
Max	0.712	0.811	0.686	0.744
Min	0.434	0.521	0.554	0.501
Ratio	1.64	1.56	1.24	1.49

While the gamma-only dosimeter gives relatively consistant readings for a given weapon spectrum regardless of orientation or dosimeter location, there is a poor correlation between dosimeter reading and marrow dose if the fraction of dose due to neutrons is altered appreciably. Comparison of the response of the gamma-only dosimeter in terms of bone marrow dose for a fallout field and the SAI spectrum is given in Table IX for three dosimeter locations on STANDING man. These values of R_m are smaller than those for R'_m in Table VI because of attenuation of the FIA dose at the dosimeter locations. The ratios of R_m values in Table IX for the two types of radiation field are seen to be approximately two, which is an unacceptably large uncertainty in measurement of dose to personnel.

Table IX: Comparison of the Response R_m of a Gamma-only Dosimeter to Fallout and the SAI Spectrum

	CHEST	BACK	WRIST OUT
SAI Spectrum	0.604	0.583	0.56
Fallout (2 days)	1.21	1.14	1.36
Ratio	2.00	1.96	2.44

SUMMARY

Efforts to improve on earlier responses of the phosphor/polyethylene TLDs to neutrons in the 1-MeV energy region have met with limited success. Small increases in response have resulted from reduction in phosphor grain size to below 2 μm and from substitution of $CaSO_4$:Tm with CaF_2:Mn or CaF_2:Dy, but the responses at 1 MeV remain well below those for ^{60}Co gammas and for 14.9-MeV neutrons in terms of absorbed energy in the dosimeters. Reasons for these relatively low responses are not fully understood but appear to be related to the higher LET for the knock-on protons relative to electrons, and to the diffusion of charge carriers between the phosphor and the polyethylene during irradiation. Further investigations would be required to understand the mechanisms involved and thereby realize the potential for improvement in sensitivity.

Gamma and neutron doses received by the bone marrow and also at various possible dosimeter locations on the body of Reference Man, for different orientations and postures of the body with respect to a hypothetical weapon burst, have been combined with experimentally measured dosimeter response functions to calculate the expected dosimeter responses in terms of bone marrow dose. Because of attenuation in the body the dose at the dosimeter locations is, on the average, higher than the actual bone marrow dose for both γ-rays and neutrons. The flat-response SAI-type dosimeter thus indicates a dose which is somewhat higher than the bone marrow dose, whereas the relatively low response of the TLDs to neutrons, combined with a high response

to gammas, results in an average overall indication of dose which approximates that received by the bone marrow from a weapon spectrum. Of more importance, however, is that there be a consistent relationship between dosimeter readings for different types of radiation fields. In this respect the SAI dosimeter is generally superior, giving a FIA response to a pure gamma spectrum which differs by less than 20% from that produced by a weapon spectrum, whereas the reading given by the DREO phosphor/polyethylene TLDs can be up to 70% larger in a pure gamma field, as is seen in Table VI. So far as a weapon spectrum is concerned the calculations suggest that the most realistic estimate of the bone marrow dose received, regardless of posture or orientation at the time of exposure, would be obtained by the use of two dosimeters, one on the CHEST and the other on the BACK.

Consideration has also been given to the relative biological effectiveness (RBE) of the different components of the incident spectrum, the dose measured by the dosimeter being expressed as a fraction of the biologically effective dose absorbed in the bone marrow. This modification further widens the already-apparent disparity between the response of the TLDs to a weapon-type spectrum as compared with that to a pure gamma or fall-out spectrum. This disparity is related to the fact that, since the TLDs give a measure of the combined dose due to gamma rays and neutrons, a degree of freedom is lost and it is not possible to adjust the relative contribution of the two dose components, as would be the case if the two components were measured separately.

The response of a dosimeter which is sensitive only to gamma rays has also been investigated as a potential means of obtaining a measure of the total dose to the bone marrow produced by a combined flux of both gamma rays and neutrons. While the relative variations in response of this dosimeter as a function of angular orientation or posture of the body were no greater than those for a dosimeter which is sensitive to both γ-rays and neutrons, the response to a pure gamma spectrum was approximately twice as great as that to a mixed spectrum, and thus this type of dosimeter is not a practical alternative to be considered.

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13. ABSTRACT

Efforts to improve the responses of phosphor/polyethylene TLDs to neutrons in the 1-MeV range have been only partially successful. Some increases in response have resulted from reduction of phosphor grain size and substitution of $CaSO_4$:Tm with CaF_2:Mn or CaF_2:Dy. Reasons for the continuing low response are not fully understood.

Calculated responses of the TLDs, when located on the body, show a closer correlation with the dose received by the bone marrow as a result of exposure to a weapon spectrum than is evident for the case of flat-response dosimeters. However the TLDs exhibit a greater difference in their response to a weapon spectrum as compared with that to a pure gamma spectrum than is the case for a flat-response dosimeter. The disparity becomes even larger when the dose measured by the dosimeters is expressed in terms of the biologically effective dose absorbed in the bone marrow. Investigation of the ability of a dosimeter, which is sensitive only to γ-rays, to provide a measure of the total bone marrow dose produced by a combined flux of γ-rays and neutrons, indicates that there is an unacceptable difference between the response to a pure gamma spectrum and that to a mixed spectrum from a weapon.

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